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The Multiwire Shielded Array—Theory and Code

by Michael J. Vrabel



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U.S. Army Electronics Research  
and Development Command  
Harry Diamond Laboratories  
Adelphi, MD 20783

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tioning from the single to the multiple wire shielded cable.  
The approach is based on the solution of the infinite line  
problem by using electromagnetic theory and a generalization to  
the finite cable by using electric circuit theory.

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## 1. INTRODUCTION

The Harry Diamond Laboratories (HDL) has been studying electromagnetic pulse (EMP) vulnerability assessment and hardening of critical Army tactical systems under the Multiple Systems Evaluation Program (MSEP). An integral requirement of this program is the development of a sufficient technical base so that a rigorous characterization can be made of all system encountered penetration sources. This report is intended to provide the basis for the development of a multiwire shielded cable capability--a significant and needed program advancement. The results of this effort, the theory, an operational computer code, and a comparison of theory and experimental data are presented.

## 2. THEORY

The solution to the multiwire shielded cable problem is based on both electromagnetic and electric circuit theory. The approach followed treats the cable as an infinitely long lossless transmission line and solves the resultant problem by using electromagnetic theory. The solution is extended to the finite cable by introducing cable end loading and treating the system as an electric circuit problem. The immediate goal is to reduce the multiwire cable to a Thevenin or Norton equivalent circuit.

A single-wave component on a lossless, infinite transmission line can be written in the standard form

$$I_w = I_e^{j(\omega t - \beta z)} \quad , \quad (1)$$

where  $I_w$  is the current representation of the wave. It is a consequence of transmission line theory that the field associated with this wave can be described using steady-state theory. And it is through the judicious application of steady-state theory that the relationship between the current and voltage on a multiwire transmission line can be developed. The wave nature of the signal will be initially disregarded; that is, the treatment will assume  $t = 0$  and  $z = 0$ . This approach permits a simplification of the equations without detracting from their applicability. The wave nature of the signal will be reintroduced at the appropriate point. As is generally the case with all transmission line developments, it is assumed that the minimum wavelength of interest is much longer than the radial dimension of the line.

The Gauss flux law in a dielectric medium is given (in mks units) by

$$\int_{\text{closed } S} \vec{D} \cdot \vec{ds} = \sum_N Q_N \quad (2)$$

The  $\sum_N Q_N$  is the charge within the volume element  $S$  and for the geometry to be considered is equal to  $I/v$ , where  $I$  is the line current and  $v$  is the propagation velocity.

The relationship between electric displacement and potential is

$$v = \frac{1}{\epsilon\epsilon_0} \int \vec{D} \cdot \vec{dl} \quad (3)$$

A shielded cable with a single eccentric inner conductor can be treated as two parallel lines by using the method of images. The relationship between cable geometry and line-image position is given by<sup>1</sup>

$$b = (a_2^2 - a_1^2 - D^2)/D \quad (4)$$

where

$b$  = wire center to image center distance,

$a_2$  = coaxial cable inner radius,

$a_1$  = wire radius,

$D$  = wire center to coaxial cable center distance.

For a wire-image pair with charge per unit length of  $Q_A$  and  $-Q_A$ , from equations (2) and (3) it can be shown that for any point external to the conductors

$$V_A = I_A (2\pi\epsilon^{1/2}\epsilon_0 c)^{-1} \ln \left( \frac{r_2}{r_1} \right) \quad (5)$$

---

<sup>1</sup>R. W. P. King, *Transmission Line Theory*, McGraw-Hill Book Co., Inc., New York (1955), 34.

where  $r_1$  and  $r_2$  are the normal radii vectors from conductor centers to the field point.

From the superposition principle, the potential at any field point for a shielded cable composed of an array of NCON wires is

$$V = \sum_{M=1}^{NCON} V_M \quad (6)$$

For the potentials at the wire surfaces and the shield (the only values of interest), from equations (5) and (6),

$$V_N = \frac{60}{\epsilon^{1/2}} \sum_{M=1}^{NCON} I_M \ln \left( \frac{r'_{NM}}{r_{NM}} \right); \quad N = 1, 2, \dots, NCON + 1, \quad (7)$$

where

$r'_{NM}$  = distance between Nth conductor and image of Mth conductor,

$r_{NM}$  = distance between Nth and Mth conductors--for  $N = M$ ,  $r_{NM}$  = radius of conductor N,

$NCON + 1$  = shield designation

Redefining terms in equation (7),

$$V_N = \sum_{M=1}^{NCON} Z_{NM} I_M \quad (8)$$

In cylindrical coordinates,  $Z_{NM}$  becomes

$$Z_{NM} = \frac{60}{\epsilon^{1/2}} \ln \left[ \frac{r_N^2 + r^2 - 2r_N r \cos \theta}{r_N^2 + r_M^2 - 2r_N r_M \cos \theta} \right]^{1/2}, \quad (9)$$

where

$r_N$  = radius vector to conductor N,

$r$  = radius vector to image of conductor M,



$\theta$  = angle defined by radii vectors to conductors N and M,

$r_M$  = radius vector to conductor M.

From equation (4), the impedance matrix terms,  $Z_{NM}$ , can be defined in terms of cable geometry.

Equation (8) is the relationship between wire current and cable potential for the infinitely long multiwire shielded line. To uniquely define both variables, it is necessary to introduce additional conditions on the cable solution to establish either  $V_N$  or  $I_N$ . The energy per unit cable length of the multiwire shielded cable is

$$U = \frac{\epsilon}{c} \sum_{N=1}^{NCON} (V_N - V_S) I_N, \quad (10)$$

where  $V_S$  = the potential at the shield. From equation (8),

$$U = \frac{\epsilon}{c} \sum_{N=1}^{NCON} \sum_{M=1}^{NCON} (Z_{NM} - Z_{SM}) I_M I_N, \quad (11)$$

where  $Z_{SM}$  are the impedance matrix terms for wires M,  $M = 1, 2, \dots, NCON$ , to shield. The relative current distribution among the wires is established by requiring that the distribution insure a minimum value for equation (11).

For the array of NCON wires, the impedance to shield for a single wire is

$$ZW_N = \frac{1}{I_N} \sum_{M=1}^{NCON} (Z_{NM} - Z_{SM}) I_M, \quad (12)$$

where

$ZW_N$  = wire N impedance to shield,

$I_N, I_M$  = relative current on wires N and M.

The impedance of the wire bundle to shield is

$$1/ZW_B = \sum_{N=1}^{NCON} 1/ZW_N, \quad (13)$$

where

$ZW_B$  = wire bundle to shield impedance.

An equivalent single conductor coaxial cable can be defined by requiring

$$ZW_B = \frac{1}{2\pi} \left( \frac{\mu_0}{\epsilon\epsilon_0} \right)^{\frac{1}{2}} \ln \left( \frac{b}{a} \right) , \quad (14)$$

where

$\mu_0$  = permeability of free space,

$b$  = inner radius of shield,

$a$  = radius of equivalent inner conductor.

The current on the single conductor coaxial cable,  $I_T$ , is related to the current on the multiwire cable by

$$I_T = \sum_{N=1}^{NCON} I_N . \quad (15)$$

The problem of establishing the absolute values for the wire currents is reduced to establishing the current on a single conductor coaxial cable.

At this point, it is appropriate to introduce cable end loading and, as a consequence, make all variables an explicit function of time. The treatment of the finite length cable requires the introduction of a two-component signal,

$$V_N(t) = V_N^+(t) + V_N^-(t) , \quad (16)$$

$$I_N(t) = I_N^+(t) - I_N^-(t) . \quad (17)$$

Although all variables should include a spatial dependence as well as a temporal dependence, since it is the signal at one cable end that is of interest, all terms are assumed to reference this point. By definition,  $V_N^+$  and  $I_N^+$  are identified as  $V_N$  and  $I_M$  of equation (8) and are independent of cable end loading. The quantities  $V_N^-$  and  $I_N^-$  are required to insure that the boundary conditions introduced by cable end loading yield the proper value for current ( $I_N$ ) through and potential ( $V_N$ ) across all wire loads. The superscripted positive and negative terms can be viewed as being associated with an incident wave and a reflected wave.

If  $I_T$  of equation (15) is known, then  $V_N^+$  and  $I_N^+$  are established. Determining the time dependence of  $I_T$  is beyond the scope of this work. The theory presented here assumes the availability of a single-conductor coaxial cable code. The intent of this development is to make maximum use of a sophisticated computer code, FREFLD,\* available at HDL. By applying FREFLD to the coaxial cable of equation (14) terminated into its characteristic impedance, the time dependence of  $I_T$  and thus  $V_N^+(t)$  and  $I_N^+(t)$  can be calculated.

The potential across an inductor with a series resistance,  $R$ , is

$$V_L(t) = L \frac{dI(t)}{dt} + RI(t) \quad (18)$$

Equation (18) can be written in an incremental time form:

$$\int_{t_N}^{t_{N+1}} V_L(t) dt = R \int_{t_N}^{t_{N+1}} I(t) dt + L \int_{t_N}^{t_{N+1}} \frac{dI(t)}{dt} dt \quad (19)$$

$$V_L(t_{N+1}) = \left(R + \frac{2L}{\Delta t}\right)I(t_{N+1}) + \left(R - \frac{2L}{\Delta t}\right)I(t_N) - V_L(t_N) \quad (20)$$

where

$$\Delta t = t_{N+1} - t_N \ll 1/f_{\max} \quad ,$$

$f_{\max}$  = maximum frequency of interest in final coaxial cable solution.

---

\*FREFLD is a coaxial cable code designed to deal with the multiplicity of coupling problems encountered in an EMP environment. FREFLD represents the work of Robert F. Gray of HDL.



Similarly, for a capacitor with a series resistance

$$V_C(t) = RI(t) + \frac{Q(t)}{C} , \quad (21)$$

$$V_C(t_{N+1}) = \left(R + \frac{\Delta t}{2C}\right)I(t_{N+1}) + \left(-R + \frac{\Delta t}{2C}\right)I(t_N) + V_C(t_N) . \quad (22)$$

For a resistor,

$$V_R(t_{N+1}) = RI(t_{N+1}) . \quad (23)$$

For an L, an R, or a C network, the potential difference at a time,  $t_{N+1}$ , is related to the current and the potential difference at a previous time,  $T_N$ , by a relationship of the general form

$$V(t_{N+1}) = A_1 I(t_{N+1}) + A_2 I(t_N) + A_3 V(t_N) . \quad (24)$$

Although not proven here, the relationship of equation (24) is quite general and can be extended to a number of other circuit elements.

A solution to the finite length multiwire shielded cable problem can now be developed. Initially, all end loading is restricted to terminations obeying the relationship of equation (24), either wire to wire or wire to shield. For an incremental time solution, all quantities that are a function of  $T_N$  are known; thus, equation (24) can be written as

$$V_M(t_{N+1}) = VEE(M,1)I_M(t_{N+1}) + VEE(M,2); M = 1, 2, \dots, M_{\max} , \quad (25)$$

$$(NCON/2) \leq M_{\max} \leq NCON ,$$

where

$M$  = wire load designation,

$$VEE(M,2) = A_{2M}I_M(t_N) + A_{3M}V_M(t_N) .$$

For circuit load M between cable wires A and B, the following boundary conditions hold:

$$I_M(t_{N+1}) = I_A^+(t_{N+1}) - I_A^-(t_{N+1}) = I_B^-(t_{N+1}) - I_B^+(t_{N+1}) , \quad (26)$$

$$V_M(t_{N+1}) = V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1}) . \quad (27)$$

Two of the NCON set of simultaneous equations that define the multiwire cable solution are, from equations (25) to (27),

$$\begin{aligned} & V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1}) \\ & = VEE(M,1) [I_A^+(t_{N+1}) - I_A^-(t_{N+1})] + VEE(M,2) , \end{aligned} \quad (28)$$

$$\begin{aligned} & V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1}) \\ & = VEE(M,1) [I_B^-(t_{N+1}) - I_B^+(t_{N+1})] + VEE(M,2) . \end{aligned} \quad (29)$$

Substituting equation (8) into equation (28) and regrouping terms,

$$\begin{aligned} & (Z_{A,1} - Z_{B,1}) I_1^-(t_{N+1}) + (Z_{A,2} - Z_{B,2}) I_2^-(t_{N+1}) \\ & + \dots [Z_{A,A} - Z_{B,A} + VEE(M,1)] I_A^-(t_{N+1}) \\ & + \dots (Z_{A,NCON} - Z_{B,NCON}) I_{NCON}^-(t_{N+1}) \\ & = (Z_{B,1} - Z_{A,1}) I_1^+(t_{N+1}) + \dots [Z_{B,A} - Z_{A,A} + VEE(M,1)] I_A^+(t_{N+1}) \\ & + \dots (Z_{B,NCON} - Z_{A,NCON}) I_{NCON}^+(t_{N+1}) + VEE(M,2) . \end{aligned} \quad (30)$$

All quantities on the right-hand side of the equation are known; the unknowns are  $\bar{I}_1(t_{N+1}), \dots, \bar{I}_{NCON}(t_{N+1})$ . If circuit M is tied to the shield ( $B \rightarrow NCON + 1$ ), then equations (28) and (29) reduce to equation (28) only. For a Thevenin or Norton equivalent circuit, the open-circuit voltage and the short-circuit current response of the desired wire or wire-shield pair must be calculated. This calculation requires that the appropriate circuit, M (with associated wire pair L, N or L, NCON + 1), be solved with wire loads  $R_1$  and  $R_2$  satisfying the requirement that

$$R_1 \gg \frac{1}{I_L(t)} \sum_{K=1}^{NCON} (Z_{L,K} - Z_{N,K}) I_K(t) \gg R_2 .$$

The development thus far deals with single-wire end loads obeying the relationship of equation (24). Kirchhoff's law can be used to generalize the cable solutions to include wire loads of any arbitrary array of components. At all network nodes (a node is defined in this instance as any network point common to two or more circuit elements with the definition of circuit elements including cable wires), the sum of all branch currents are zero:

$$\sum_n i_n(t) = 0 . \quad (31)$$

The sum of the voltages around any closed loop is zero:

$$v_{ab}(t) + v_{bc}(t) + v_{cd}(t) + v_{da}(t) = 0 . \quad (32)$$

When the loop includes a wire pair or a wire-shield pair, equation (32) becomes

$$v_{ab}(t) + v_{bc}(t) + v_{cd}(t) = V_a(t) - V_d(t) , \quad (33)$$

where a and d designate the conductor pair.

Kirchhoff's law can be used to develop an  $n \times n$  array of simultaneous equations to solve for the instantaneous branch currents for any wire loading networks, where  $n$  represents the total number of unknown branch currents. It should be recalled from equation (30) that, when the branch represents a cable wire, the branch current solution is for a single component of the wire current,  $\bar{I}$ .



At the cable end, the emergence of the wire bundle from the well-defined transmission line geometry and its entry into the random geometry associated with the wire terminations does not eliminate the mutual wire interactions. At the terminations, these interactions can be characterized by the lumped parameter model of mutual inductance.\* For two wire circuits with inductances  $L_A$  and  $L_B$ , the potentials across  $L_A$  and  $L_B$  are

$$V_A = L_A \frac{di_A}{dt} + K(L_A L_B)^{1/2} \frac{di_B}{dt} , \quad (34)$$

$$V_B = L_B \frac{di_B}{dt} + K(L_A L_B)^{1/2} \frac{di_A}{dt} . \quad (35)$$

Introducing operational notations, where  $p^n \equiv d^n/dt^n$ , equations (34) and (35) become

$$V_A = pL_A i_A + pK(L_A L_B)^{1/2} i_B , \quad (36)$$

$$V_B = pL_B i_B + pK(L_A L_B)^{1/2} i_A , \quad (37)$$

where  $K$  (the coupling coefficient) is a dimensionless parameter with a value obeying  $|K| \leq 1$  and is a function of wiring geometry.

Equations (36) and (37) can be rewritten in the general form:

$$V_A = z_{AA} i_A + z_{AB} i_B , \quad (38)$$

$$V_B = z_{BA} i_A + z_{BB} i_B , \quad (39)$$

where

$$z_{AB} = z_{BA} .$$

---

\*To be rigorous, one should include the capacitive coupling terms between all conductors. Cable loading geometry and frequency spectrum rarely permit these terms to be other than insignificant.

For a cable with  $m$  wire load networks ( $m \leq NCON$ ),

$$V_N = \sum_{M=1}^m z_{NM} i_M ; N = 1, 2, \dots, m , \quad (40)$$

where

$$z_{NM} = p K_{NM} (L_N L_M)^{\frac{1}{2}} ,$$

$$K_{NN} = 1 ,$$

and lowercase letters are used to distinguish the matrix terms of equation (40) from the cable matrix terms of equation (8).

To introduce wire-load mutual inductance into the cable solution matrices, to the network array equations defining the cable end loads must be added equation (40). The most severe problem posed by introducing equation (40) is establishing the value of the coupling coefficients,  $K_{NM}$ .

Equation (40) can be rewritten in the form of an incremental time expression:

$$V_K(t_{N+1}) = \sum_{M=1}^m \left[ \frac{2K_{KM}}{\Delta t} (L_K L_M)^{\frac{1}{2}} I_M(t_{N+1}) - \frac{2K_{KM}}{\Delta t} (L_K L_M)^{\frac{1}{2}} I_M(t_N) - V_M(t_N) \right] , \quad (41)$$

$$V_M(t_N) = 0 \text{ for } M \neq K .$$

If equation (41) is substituted for the expression given by equation (24), then the special case of inductive wire loads (with both self and mutual inductance effects) can be solved. For a load of the form of equation (41), equation (25) becomes

$$\begin{aligned}
& V_A^+(t_{N+1}) - V_B^+(t_{N+1}) + V_A^-(t_{N+1}) - V_B^-(t_{N+1}) \\
& = \sum_{M=1}^m \left\{ VEE(M,1) \left[ I_M^+(t_{N+1}) - I_M^-(t_{N+1}) \right] + VEE(M,2) \right\} . \quad (42)
\end{aligned}$$

From this expression, the array of simultaneous equations required to solve for  $I_M$  can be derived in a manner analogous to the derivation of equation (31). For the general loading condition of mutual inductance incidental to a set of arbitrary wire load, Kirchhoff's laws can be introduced as indicated previously.

The development thus far ignores all wire terminations at the far cable end. For a straight cable of physical length  $L$ , assuming that the propagation velocity external to the cable is  $c$ , the time delays between the initial arrival of the signal at the near end and reflection from the far cable end for three illumination conditions are

$$T_1 = \frac{L}{c} (\epsilon^{\frac{1}{2}} - 1) , \quad (43)$$

$$T_2 = \frac{L}{c} (\epsilon^{\frac{1}{2}} + 1) , \quad (44)$$

$$T_3 = \frac{L}{c} \epsilon^{\frac{1}{2}} , \quad (45)$$

where

$\epsilon$  = cable dielectric constant,

$T_1$  = time delay for cable illumination from far end,

$T_2$  = time delay for cable illumination from near end,

$T_3$  = time delay for broadside illumination.

These equations represent the maximum time duration for the specified illumination conditions for which the single-end cable solutions are valid. If  $V_N^A$  is the potential across load  $N$  at cable end  $A$  (with a corresponding current  $I_N^A$ ) and  $V_N^B$  is the potential across load  $M$  (across the identical conductor<sup>N</sup>pair) at the other cable end,  $B$ , then

$$V_N^A(t) = V_N^{A+}(t) + V_N^{A-}(t) + V_N^{B-}(t - T) , \quad (46)$$

$$V_N^B(t) = V_N^{B+}(t) + V_N^{B-}(t) + V_N^{A-}(t - T) , \quad (47)$$

where

$$T = \frac{L}{c} \epsilon^{\frac{1}{2}} ,$$

$$V_N^{B-}(t - T) = V_N^{A-}(t - T) = 0, \text{ for } t < T .$$

By introducing the requirements of equations (46) and (47) (or the corresponding relationships between the current components) into the set of simultaneous equations necessary to solve the multiwire problem, a solution can be derived without time duration restrictions.

A common multiwire cable construction technique involves arranging all wires (or twisted wire pairs) on concentric cylindrical layers. This generally involves a different lay for each wire layer. Although all wires preserve their location with respect to all remaining wires on the same layer and with respect to the shield, the distance between wires on different layers becomes a function of location along the cable. The logarithmic relationship between wire distances and the magnitude of the impedance matrix terms  $Z_{NM}$  preclude any nearest neighbor approximation in the treatment of the multiwire cable problem. However, as can be seen from equation (7), this logarithmic relationship also insures that the response of any conductor is relatively insensitive to any deviation in the relative positioning of the wires among the layers. If the differential lay among all wire layers is sufficient to insure a full  $2\pi$  rotation over a cable length shorter than the maximum frequency of interest, then signal averaging can be used to eliminate lay effects. Signal averaging involves a sufficient number of solutions of the simultaneous equation matrix for each value of  $t_N$  with a systematic variation in angular position of all wire layers to insure a good approximation to the continuous distribution of wire positions along a cable.

Finally, equation (4) poses a singularity problem for wire coinciding with the cable center. This singularity can be avoided by offsetting the central axis wire.



### 3. COMPUTER CODE

The multiconductor cable code characterizes the response of a wire pair or a wire-to-shield combination by outputting the open-circuit voltage and short-circuit current. These are sufficient data to develop either a Thevenin or Norton equivalent circuit. All remaining wires must be end loaded with a single R, L-R, or C-R series network. Far-end cable reflections are not included. The code permits the inclusion of from 1 to 59 wires arranged on a maximum of four layers centrosymmetric with respect to the cable axis. These limits can be expanded by minor code modifications. The code contains the user option of wire lay averaging (ROTA = 1) and can be used to establish all the fundamental infinite cable parameters.

To supplement the code comment cards, several additional statements are required.

a. All wires are numbered sequentially from 1 through NCON, starting at the innermost layer (fig. 1).

b. All wire layers are numbered starting from the innermost layer.

c. "MR" designates a single wire number for the desired Thevenin equivalent pair, or the wire number for a wire-shield combination.

d. The shield designation number, LCON, is NCON + 1.

e. The designated load for the MR associated conductor pair must be 50 k $\Omega$ .

f. If the conductor of any pair is the shield, its node value must be listed after the wire node number.

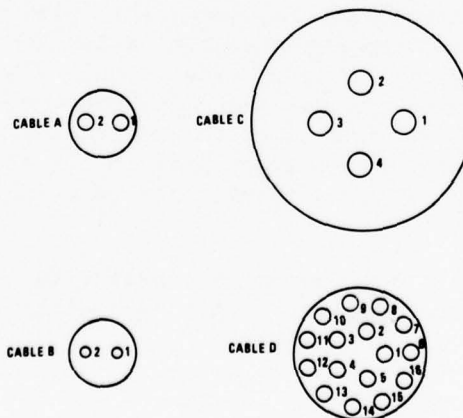


Figure 1. Cross section of shielded multiwire test cables.

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Multiconductor cable code

```

DIMENSION R1(60), R2(60), ANGA(3600), Z(60,60), ZS(60)
DIMENSION ZP(60,60), RV(4), COEFL(3600), COEFR(60), RN(4)
DIMENSION CURNT(60), CUR(5), AMP(60), POWER(60), TPOW(8000)
DIMENSION CUPOS(200), ATIM(200), WIRED(60,200), WIREB(60,200)
DIMENSION DW(60), CUB(60), DIGIT(200), DIGT(100), DIGA(100)
DIMENSION ARAY(6000), TERM(600,5), TERMA(600,6), VOLTA(60,5)
DIMENSION MREG(60), WIREC(60,200), WIREE(60,200), VEE(60,6)
DIMENSION WIREF(60,200), WIREG(60,200)
DIMENSION FVOLT(200), FCURR(200), VSHLD(200)
DIMENSION KREG(60), LREG(60), PCTR(100), SCTR(100)
DIMENSION XLAB(10), YLAB(10), YLAC(10), YLAD(10)
DIMENSION PTLAB(20), PTLAC(20), PTLAD(20)
DIMENSION ZTIME(200), ZTHEV(200), MAR(20)
DIMENSION BURNT(60), ZZIMP(60), CURR(4,8000), CUA(4), CU(4)
DIMENSION LZ(4), UP(3), BOT(3), KUP(3), KBOT(3), LRN(4)
DIMENSION CAPC(50), CAPD(50), PTLAE(10), PTLAF(10), ZAX(10)
DIMENSION XAX(10), YAX(10), SUBAA(10), XYX(200), YXY(200)
DIMENSION TYME(200), CURRN(200), VOLTN(200), CURRM(200)
DIMENSION VEA(60,6), ERF(60), EFR(60), VOLTM(200)

C
  NAMELIST/LISTA/ARRAY,LIM,DELT,RV,RN,DW,DC,DI,KK,MR,DIGIT,
  &TDUR,ROTA,XLAB,YLAB,PTLAB,PTLAC,YLAC,MAR,NMAR,YLAD,PTLAD,PLDT,
  &EXAX,YAX,SUBAA,CAPC,CAPD,PTLAE,PTLAF,ZAX,BPLOT,TYME
C
  WRITE(6,54)
54  FORMAT(' A PROGRAM FOR DEVELOPING A THEVENIN EQUIVALENT FOR A MULT
  &I WIRE SHIELDED CABLE UNDER REACTIVE END LOADING CONDITIONS'//)
C
  READ(5,LISTA)

C
C  LAY IS THE LAYER NUMBER TO UNDERGO NO ROTATION
C
C  RV(K)=RADIUS VECTOR TO LAYER K
C
C  RN(K)=NUMBER OF CONDUCTORS IN LAYER K
C
C  DW=INDIVIDUAL WIRE RADIUS
C
C  DC=INNER RADIUS OF COAX SHIELD
C
C  DI=DIELECTRIC CONSTANT
C
C  KK=NUMBER OF WIRE LAYERS
C
C  MR IS THE NUMBER OF THE WIRE FOR WHICH THE THEVENIN EQUIVALENT IS DEVELOPED
C
C
C
  WRITE(6,61)RV
61  FORMAT(10X,33H RADIUS VECTORS TO WIRE LAYERS ARE/10X,4F6.3//)
  WRITE(6,55)RN
55  FORMAT(10X,35H NO. OF CONDUCTORS IN EACH LAYER ARE/10X,4F6.0//)
  WRITE(6,56)(DW(I),I=1,60)
56  FORMAT(10X,29H THE INDIVIDUAL WIRE RADII ARE/10X,10F6.3//)
  WRITE(6,57)DC
57  FORMAT(10X,30H INNER RADIUS OF COAX SHIELD IS/10X,F6.3//)

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WRITE(6,58)DI
58  FFORMAT(10X,26HTHE DIELECTRIC CONSTANT IS/10X,F6.3//)
WRITE(6,59)MR
59  FFORMAT(10X,46HWIRE NUMBER FOR THEVENIN EQUIVALENT CIRCUIT IS/10X,I
    &2//)
WRITE(6,240)
240  FFORMAT(' ')
      DO 2 K=1,KK
      KKK=RN(K)
      IF(KKK)1,2,1
1      DO 3 J=1,KKK
      L=1+L
      R1(L)=RV(K)
3      CONTINUE
2      CONTINUE
      L=0
      DO 4 K=1,KK
      KKK=RN(K)
      IF(KKK)6,4,6
6      DO 5 J=1,KKK
      L=1+L
      R2(L)=R1(L)+(DC**2-DW(L)**2-R1(L)**2)/R1(L)
5      CONTINUE
4      CONTINUE
      DO 7 K=1,KK
      COND=COND+RN(K)
7      CONTINUE
      NCON=COND
      DO 426 MG=1,KK
      EGG=EGG+RN(MG)
      AMR=MR
      IF(EGG-AMR)426,425,425
425  LAY=MG
      GO TO 427
426  CONTINUE
427  PI=3.14159
      N=0
      DO 9 K=1,KK
      KKK=RN(K)
      IF(KKK)10,9,10
10     DO 8 M=1,KKK
      N=1+N
      BB=M
      ANGA(N)=2.*PI*(BB-1.)/RN(K)
8      CONTINUE
9      CONTINUE
      DO 13 K=1,NCON
      DO 14 M=1,NCON
      IF(K-M)11,12,11
12     Z(K,M)=(60./DI**0.5)*ALOG((R2(K)-R1(K))/DW(K))
      GO TO 29
11     Z(K,M)=(60./DI**0.5)*ALOG(((R1(K)**2+R2(M)**2-2.*R1(K)*R2(M)*
      COS(ANGA(K)-ANGA(M)))/(R1(K)**2+R1(M)**2-2.*R1(K)*R1(M)*COS(
      ANGA(K)-ANGA(M))))**0.5)
29     CONTINUE
14     CONTINUE
13     CONTINUE
      LCON=NCON+1
      DO 15 M=1,NCON
      ZS(M)=(60./DI**0.5)*ALOG(((DC**2+R2(M)**2-2.*DC*R2(M)*

```

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```

ECDS(ANGA(M)))/(DC**2+R1(M)**2-2.*DC*R1(M)*COS(
EANGA(M)))**0.5)
Z(LCON,M)=ZS(M)
15  CONTINUE
    DO 16 K=1,NCON
    DO 17 M=1,NCON
    ZP(K,M)=Z(K,M)-ZS(M)
17  CONTINUE
16  CONTINUE
    IF(KK-1)716,717,716
717  DO 718 MM=1,NCON
    CJB(MM)=1./RN(1)
718  CONTINUE
    GO TO 719
716  DO 218 ME=1,4
    IF(RN(ME))218,219,218
219  RV(ME)=1.
218  CONTINUE
    NYC=0
    PICA=1.
419  DO 400 NEM=1,20
    RED1=NEM
    IF(NYC)451,452,451
451  CUR(1)=CU(1)-0.1*(RED1-10.)/PICA
    GO TO 455
452  CUR(1)=2.-0.1*(RED1-1.)
455  IF(2-KK)401,402,402
401  DO 400 NEN=1,20
    RED2=NEN
    IF(NYC)454,458,454
458  CUR(2)=1.-0.1*(RED2-1.)
    GO TO 403
402  CUR(2)=1.-CUR(1)
    GO TO 407
454  CUR(2)=CU(2)-0.1*(RED2-10.)/PICA
403  CONTINUE
    IF(3-KK)404,405,405
404  DO 400 NEP=1,20
    RED3=NEP
    IF(NYC)457,456,457
456  CUR(3)=1.-0.1*(RED3-1.)
    GO TO 406
405  CUR(3)=1.-CUR(1)-CUR(2)
    GO TO 407
457  CUR(3)=CU(3)-0.1*(RED3-10.)/PICA
406  CONTINUE
    CUR(4)=1.-CUR(1)-CUR(2)-CUR(3)
407  CONTINUE
    KM=0
    DO 408 JJ=1,KK
    KKK=RN(JJ)
    DO 408 LL=1,KKK
    KM=1+KM
    AMP(KM)=CUR(KK+1-JJ)/RN(JJ)
408  CONTINUE
    MB=1+MB
    DO 423 MA=1,KK
    CJRR(MA,MB)=CUR(KK-MA+1)
423  CONTINUE
    DO 409 NA=1,NCON

```



```

      DO 410 MA=1,NCON
      POWER(MA)=ZP(MA,MA)*AMP(MA)*AMP(MA)+POWER(MA)
410  CONTINUE
409  CONTINUE
      DO 411 NB=1,NCON
      TPOW(NB)=POWER(NB)+TPOW(MB)
      POWER(NB)=0.
411  CONTINUE
400  CONTINUE
      WRITE(6,412)
412  FORMAT(' RELATIVE CURRENT DISTRIBUTION ON SINGLE WIRE OF EACH LAY
      ER FOR I+ COMPONENT')
      WRITE(6,413)
413  FORMAT('          LAYER 1          LAYER 2          LAYER 3          LAYER 4
      ( RELATIVE ENERGY')
      MEE=0
      DO 414 MD=1,10
      POWE=TPOW(1)
      KAPPA=1
      NAT=MB-1
      DO 415 MC=1,NAT
      IF (POWE-TPOW(MC+1))415,415,416
416  POWE=TPOW(MC+1)
      KAPPA=MC+1
415  CONTINUE
      MEE=1+MEE
      TPOW(KAPPA)=1.0E+06
      CU1=CURR(1,KAPPA)/RN(1)
      CU2=CURR(2,KAPPA)/RN(2)
      CU3=CURR(3,KAPPA)/RN(3)
      CU4=CURR(4,KAPPA)/RN(4)
      IF (MEE-1)421,418,421
418  DO 424 MA=1,KK
      CU(MA)=CURR(KK-MA+1,KAPPA)
      CJA(MA)=CURR(MA,KAPPA)/RN(MA)
424  CONTINUE
421  WRITE(6,417)CU1,CU2,CU3,CU4,POWE
417  FORMAT(10X,E10.4,2X,E10.4,2X,E10.4,2X,E10.4,2X,E12.6)
414  CONTINUE
      DO 422 LAR=1,MB
      TPOW(LAR)=0.
422  CONTINUE
      MB=0
      PICA=4.*PICA
      NYC=1
      MAA=1+MAA
      IF (MAA-3)419,419,420
420  CONTINUE
      JA=0
      DO 429 NS=1,KK
      KKK=RN(NS)
      DO 429 MS=1,KKK
      JA=1+JA
      CJB(JA)=CUA(NS)
429  CONTINUE
719  MU=0
      DO 225 KX=1,KK
      MV=RN(KX)
      DO 225 MX=1,MV
      MJ=1+MU

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      IF(KX-2)226,227,228
226  CURNT(MU)=CUA(1)
      GJ TJ 225
227  CURNT(MU)=CUA(2)
      GU TO 225
228  IF(KX-4)229,230,230
229  CURNT(MU)=CUA(3)
      GJ TO 225
230  CURNT(MU)=CUA(4)
225  CONTINUE
      MPP=1+MPP
      IF(MPP-1)237,236,237
236  DD 234 JA=1,NCON
      DD 233 KA=1,NCON
      BURNT(KA)=CURNT(KA)
      IF(BURNT(KA))231,232,231
232  BURNT(KA)=1.0E-08
231  ZZIMP(JA)=ZP(JA,KA)*BURNT(KA)/BURNT(JA)+ZZIMP(JA)
233  CONTINUE
      ZZINV=1./ZZIMP(JA)+ZZINV
234  CONTINUE
      ZPOS=1./ZZINV
      WRITE(6,235)ZPOS
235  FORMAT(10X,52HWIRE BUNDLE TO SHIELD IMPEDANCE FOR I+ COMPONENT IS
      E,E10.4//)
237  CONTINUE
      LL=0
      DD 700 NN=1,100
      LL=1+LL
      DIGT(NN)=DIGIT(LL)
      LL=1+LL
      DIGA(NN)=DIGIT(LL)
700  CONTINUE
      MTIM=TDUR/DELT+1.0E-06
      KN=1
      MMTIM=MTIM+1
      DD 701 NN=1,MMTIM
      AA=NN
      DD 704 MM=KN,100
      IF(AA*DELT-DELT-DIGT(MM))703,702,704
702  CUPOS(NN)=DIGA(MM)
      GJ TJ 711
703  CUPOS(NN)=((DELT*(AA-1.)-DIGT(MM-1))/(DIGT(MM)-DIGT(MM-1)))*
      (DIGA(MM)-DIGA(MM-1))+DIGA(MM-1)
      GJ TO 712
704  CONTINUE
711  KN=MM
      GJ TJ 800
712  KN=MM-1
300  SS=NV
      TDU=DELT*(SS-1.)
701  CONTINUE
      DD 705 NN=1,MTIM
      AA=NN
      ATIM(NN)=AA*DELT-DELT
705  CONTINUE
      DD 706 NN=1,NCON
      DD 707 MM=1,MTIM
      WIRED(NN,MM)=CUB(NN)*CUPOS(MM)
707  CONTINUE

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```

706 CONTINUE
    DD 709 MM=1,MTIM
    DD 708 NN=1,NCON
    DD 710 JJ=1,NCON
    WIREB(NN,MM)=Z(NN,JJ)*WIRED(JJ,MM)+WIREB(NN,MM)
710 CONTINUE
708 CONTINUE
709 CONTINUE
    DD 934 MM=1,MTIM
    DD 938 JJ=1,NCON
    WIREB(LCON,MM)=ZS(JJ)*WIRED(JJ,MM)+WIREB(LCON,MM)
938 CONTINUE
934 CONTINUE
C LIM IS THE TOTAL NUMBER OF COMPONENTS OPERATED UPON + TOTAL NUMBER OF
C FINAL COMPONENTS
C ALL LOAD DATA IS READ INTO AN ARRAY: TERM(N,M), N=1,2,...10; M=1,2,...5
C M ELEMENT #1= COMPONENT TYPE; R=1, C=2, L=3, STOP=4
C           #2= FROM NODE
C           #3= TO NODE
C           #4= COMPONENT VALUE
C           #5= SERIES RESISTANCE
    KT=0
    DD 542 MT=1,LIM
    DD 542 NT=1,5
    KT=1+KT
    TERM(MT,NT)=ARRAY(KT)
    WRITE(6,588)TERM(MT,NT)
588 FORMAT(15X,E10.4)
542 CONTINUE
    INIA=1
543 INI=INIA
    IF(LIM-INIA+1)573,565,573
573 INA=INI+2
    DD 500 N=INI,INA
    M=1
    IF(4.-TERM(N,M))500,501,500
501 LAST=N-1
554 INIA=N+1
    GO TO 546
500 CONTINUE
C FOR ALL COMPONENTS V2=C1I2+C2I1+C3V1; I2=C4V2+C5I1+C6V1 - DATA STORED
C SERIALY IN ARRAY TERMA(N,M) M=1,2,...6
546 DD 559 N=INI, LAST
    IF(TERM(N,1)-2)511,512,513
511 TERMA(N,1)=TERM(N,4)
    TERMA(N,2)=0.
    TERMA(N,3)=0.
    TERMA(N,4)=1./TERM(N,4)
    TERMA(N,5)=0.
    TERMA(N,6)=0.
    GO TO 510
512 TERMA(N,1)=TERM(N,5)+DELT/(2.*TERM(N,4))
    TERMA(N,2)=-TERM(N,5)+DELT/(2.*TERM(N,4))
    TERMA(N,3)=1.
    TERMA(N,4)=1./(TERM(N,5)+DELT/(2.*TERM(N,4)))
    TERMA(N,5)=(TERM(N,5)-DELT/(2.*TERM(N,4)))/
    (TERM(N,5)+DELT/(2.*TERM(N,4)))
    TERMA(N,6)=-1./(TERM(N,5)+DELT/(2.*TERM(N,4)))
    GO TO 510
513 TERMA(N,1)=TERM(N,5)+2.*TERM(N,4)/DELT

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```

TERMA(N,2)=TERM(N,5)-2.*TERM(N,4)/DELT
TERMA(N,3)=-1.
TERMA(N,4)=1./(TERM(N,5)+2.*TERM(N,4)/DELT)
TERMA(N,5)=(-TERM(N,5)+2.*TERM(N,4)/DELT)/(TERM(N,5)+2.*
TERMA(N,4)/DELT)
TERMA(N,6)=1./(TERM(N,5)+2.*TERM(N,4)/DELT)
510 CONTINUE
559 CONTINUE
LASTA=LAST-1
566 KTD=1+KTD
DO 567 JK=1,3
VOLTA(KTD,JK)=TERMA(IN1,JK)
567 CONTINUE
DO 593 JK=4,5
VOLTA(KTD,JK)=TERM(IN1,JK-2)
593 CONTINUE
GO TO 543
565 CONTINUE
C VEE(1...KTD,1)=C1
C VEE(1...KTD,2)=C2I1 + C3V1
C VEE(1...KTD,3)= FROM NODE
C VEE(1...KTD,4)= TO NODE
C VEE(1...KTD,5)= TAG LABEL - FROM NODE
C VEE(1...KTD,6)= TAG LABEL - TO NODE
C THE REMAINING PART OF THE PROGRAM SOLVES THE SYSTEM OF SIMULTANEOUS
C LINEAR EQUATIONS RESULTING FROM THE INCLUSION OF WIRE END LOADING
C ROTA ESTABLISHES LAY AVERAGING EFFECT; 0= NO ROTATION, 1= SINGLE WIRE
C INCREMENT ROTATION
C TDJR=TOTAL TIME DURATION OF SIGNAL WAVEFORM
C DELT=DELTA TIME
DO 676 MM=1,KTD
DO 676 NN=3,4
VEE(MM,NN)=VOLTA(MM,NN+1)
576 CONTINUE
DO 627 JQ=1,KTD
VEE(JQ,1)=VOLTA(JQ,1)
VEE(JQ,5)=VOLTA(JQ,4)
VEE(JQ,6)=VOLTA(JQ,5)
KREG(JQ)=VEE(JQ,3)
LREG(JQ)=VEE(JQ,4)
527 CONTINUE
DO 600 JJ=1,2
DO 678 IR=2,MTIM
DO 626 M=1,KTD
MM=VEE(M,3)
NN=VEE(M,4)
IF (JJ-1)946,946,947
946 VEE(M,2)=VOLTA(M,2)*(WIRED(MM,IR-1)-WIREF(MM,IR-1))+
(VOLTA(M,3)*(WIREB(MM,IR-1)+WIREC(MM,IR-1))-(WIREB(NN,IR-1)+
WIREC(NN,IR-1)))
GO TO 948
947 VEE(M,2)=VOLTA(M,2)*(WIRED(MM,IR-1)-WIREF(MM,IR-1))+VOLTA(M,3)*
((WIREB(MM,IR-1)+WIREG(MM,IR-1))-(WIREB(NN,IR-1)+WIREG(NN,IR-1)))
948 CONTINUE
526 CONTINUE
IF (ROTA)428,428,675
428 GO TO 79
575 KY=0
DO 459 NN=1,KK
IF (LAY-NN)460,459,460

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```
460 KY=1+KY
    LZ(KY)=RN(NN)
    LRN(KY)=NN
459 CONTINUE
    IF(KK-3)461,462,463
463 LZ3=LZ(3)
    DJ 80 NA=1,LZ3
    UP(3)=0.
    LRN3=LRN(3)
    DD 464 KA=1,LRN3
    UP(3)=RN(KA)+UP(3)
464 CONTINUE
    BDT(3)=UP(3)-RN(LRN(3))+1.
    KUP(3)=UP(3)
    KBDT(3)=BDT(3)
    KJP3=KUP(3)
    DD 338 MM=1,KTD
    DD 338 NN=5,6
    VEA(MM,NN)=0.
338 CONTINUE
    DD 466 KA=1,KUP3
    IF(KA-KBDT(3))466,467,468
467 DD 469 KB=1,KTD
    IF(UP(3)-VEE(KB,3))470,471,470
470 IF(UP(3)-VEE(KB,4))469,472,469
471 DD 319 MM=1,KTD
    IF(KA-VEE(MM,3))320,321,320
320 IF(KA-VEE(MM,4))319,322,319
321 VEA(MM,5)=VEE(KB,5)
    GD TO 466
322 VEA(MM,6)=VEE(KB,5)
    GJ TO 466
319 CONTINUE
472 DD 323 MM=1,KTD
    IF(KA-VEE(MM,3))324,325,324
324 IF(KA-VEE(MM,4))323,326,323
325 VEA(MM,5)=VEE(KB,6)
    GD TO 466
326 VEA(MM,6)=VEE(KB,6)
    GJ TO 466
323 CONTINUE
469 CONTINUE
468 DD 473 KB=1,KTD
    BL=KA-1
    IF(BL-VEE(KB,3))475,474,475
475 IF(BL-VEE(KB,4))473,476,473
474 DD 330 MM=1,KTD
    IF(KA-VEE(MM,3))331,332,331
331 IF(KA-VEE(MM,4))330,333,330
332 VEA(MM,5)=VEE(KB,5)
    GD TO 466
333 VEA(MM,6)=VEE(KB,5)
    GJ TO 466
330 CONTINUE
476 DD 334 MM=1,KTD
    IF(KA-VEE(MM,3))335,336,335
335 IF(KA-VEE(MM,4))334,337,334
336 VEA(MM,5)=VEE(KB,6)
    GD TO 466
337 VEA(MM,6)=VEE(KB,6)
```

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```
GJ TO 466
334 CONTINUE
473 CONTINUE
466 CONTINUE
    DD 339 MM=1,KTD
    DD 339 NN=5,6
    IF (VEA(MM,NN))340,339,340
340 VEE(MM,NN)=VEA(MM,NN)
339 CONTINUE
462 LZ2=LZ(2)
    DD 80 NB=1,LZ2
    UP(2)=0.
    LRN2=LRN(2)
    DD 238 KA=1,LRN2
    UP(2)=RN(KA)+UP(2)
238 CONTINUE
    BOT(2)=UP(2)-RN(LRN(2))+1.
    KJP(2)=UP(2)
    KBOT(2)=BOT(2)
    DD 316 MM=1,KTD
    DD 316 NN=5,6
    VEA(MM,NN)=0.
316 CONTINUE
    KJP2=KJP(2)
    DD 263 KA=1,KUP2
    IF (KA-KBOT(2))263,241,242
241 DD 243 KB=1,KTD
    IF (UP(2)-VEE(KB,3))244,245,244
244 IF (UP(2)-VEE(KB,4))243,246,243
245 DD 300 MM=1,KTD
    IF (KA-VEE(MM,3))301,302,301
301 IF (KA-VEE(MM,4))300,303,300
302 VEA(MM,5)=VEE(KB,5)
    GO TO 263
303 VEA(MM,6)=VEE(KB,5)
    GO TO 263
300 CONTINUE
246 DD 304 MM=1,KTD
    IF (KA-VEE(MM,3))305,306,305
305 IF (KA-VEE(MM,4))304,307,304
306 VEA(MM,5)=VEE(KB,6)
    GO TO 263
307 VEA(MM,6)=VEE(KB,6)
    GO TO 263
304 CONTINUE
243 CONTINUE
242 DD 247 KB=1,KTD
    BL=KA-1
    IF (BL-VEE(KB,3))248,249,248
248 IF (BL-VEE(KB,4))247,250,247
249 DD 308 MM=1,KTD
    IF (KA-VEE(MM,3))309,310,309
309 IF (KA-VEE(MM,4))308,311,308
310 VEA(MM,5)=VEE(KB,5)
    GO TO 263
311 VEA(MM,6)=VEE(KB,5)
    GO TO 263
308 CONTINUE
250 DD 312 MM=1,KTD
    IF (KA-VEE(MM,3))313,314,313
```

```

313 IF (KA-VEE(MM,4))312,315,312
314 VEA(MM,5)=VEE(KB,6)
    GO TO 263
315 VEA(MM,6)=VEE(KB,6)
    GO TO 263
312 CONTINUE
247 CONTINUE
263 CONTINUE
    DJ 317 MM=1,KTD
    DD 317 NN=5,6
    IF (VEA(MM,NN))318,317,318
318 VEE(MM,NN)=VEA(MM,NN)
317 CONTINUE
461 LZ1=LZ(1)
    DD 80 NC=1,LZ1
    UP(1)=0.
    LRN1=LRN(1)
    DJ 265 KA=1,LRN1
    UP(1)=RN(KA)+UP(1)
265 CONTINUE
    BDT(1)=UP(1)-RN(LRN(1))+1.
    KJP(1)=UP(1)
    KBDT(1)=BDT(1)
    KUP1=KUP(1)
    DJ 357 MM=1,KTD
    DJ 357 NN=5,6
    VEA(MM,NN)=0.
357 CONTINUE
    DD 267 KA=1,KUP1
    IF (KA-KBDT(1))267,268,269
268 DD 270 KB=1,KTD
    IF (UP(1)-VEE(KB,3))271,272,271
271 IF (UP(1)-VEE(KB,4))270,273,270
272 DJ 341 MM=1,KTD
    IF (KA-VEE(MM,3))342,343,342
342 IF (KA-VEE(MM,4))341,344,341
343 VEA(MM,5)=VEE(KB,5)
    GO TO 267
344 VEA(MM,6)=VEE(KB,5)
    GO TO 267
341 CONTINUE
273 DJ 345 MM=1,KTD
    IF (KA-VEE(MM,3))346,347,346
346 IF (KA-VEE(MM,4))345,348,345
347 VEA(MM,5)=VEE(KB,6)
    GO TO 267
348 VEA(MM,6)=VEE(KB,6)
    GO TO 267
345 CONTINUE
270 CONTINUE
269 DJ 274 KB=1,KTD
    BL=KA-1
    IF (BL-VEE(KB,3))275,276,275
275 IF (BL-VEE(KB,4))274,277,274
276 DJ 349 MM=1,KTD
    IF (KA-VEE(MM,3))350,351,350
350 IF (KA-VEE(MM,4))349,352,349
351 VEA(MM,5)=VEE(KB,5)
    GO TO 267
352 VEA(MM,6)=VEE(KB,5)

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GO TO 267
349 CONTINUE
277 DJ 353 MM=1,KTD
      IF (KA-VEE(MM,3))354,355,354
354 IF (KA-VEE(MM,4))353,356,353
355 VEA(MM,5)=VEE(KB,6)
      GJ TO 267
356 VEA(MM,6)=VEE(KB,6)
      GO TO 267
353 CCONTINUE
274 CCONTINUE
267 CCONTINUE
      DD 358 MM=1,KTD
      DD 358 NN=5,6
      IF (VEA(MM,NN))359,358,359
359 VEE(MM,NN)=VEA(MM,NN)
358 CCONTINUE
79 CCONTINUE
      L=0
      DJ 601 M=1,NCON
      DJ 602 K=1,KTD
      KFOLD=VEE(K,5)
      LFOLD=VEE(K,6)
      IF (KFOLD-1-NCON)616,602,616
516 L=1+L
      IF (M-KFOLD)604,603,604
603 CDEF(L)=Z(KFOLD,M)-Z(LFOLD,M)+VEE(K,1)
      GO TO 602
604 CDEF(L)=Z(KFOLD,M)-Z(LFOLD,M)
602 CCONTINUE
      DD 605 K=1,KTD
      KFOLD=VEE(K,5)
      LFOLD=VEE(K,6)
      IF (LFOLD-1-NCON)617,605,617
617 L=1+L
      IF (M-LFOLD)606,607,606
607 CDEF(L)=Z(KFOLD,M)-Z(LFOLD,M)-VEE(K,1)
      GO TO 605
606 CDEF(L)=Z(KFOLD,M)-Z(LFOLD,M)
605 CCONTINUE
601 CCONTINUE
      L=0
      DD 608 M=1,KTD
      KFOLD=VEE(M,5)
      LFOLD=VEE(M,6)
      IF (KFOLD-1-NCON)618,608,618
618 L=1+L
      MREG(L)=KFOLD
      CJEFR(L)=WIREB(LFOLD,IR)-WIREB(KFOLD,IR)+VEE(M,1)*WIRED(KFOLD,IR)
      C+VEE(M,2)
608 CCONTINUE
      DD 609 M=1,KTD
      KFOLD=VEE(M,5)
      LFOLD=VEE(M,6)
      IF (LFOLD-1-NCON)610,609,610
610 L=1+L
      MREG(L)=LFOLD
      CJEFR(L)=WIREB(LFOLD,IR)-WIREB(KFOLD,IR)-VEE(M,1)*WIRED(LFOLD,IR)
      C+VEE(M,2)
609 CCONTINUE

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EPS=1.0E-07
CALL GELG(COEFR,COEFL,NCON,1,EPS,IER)
DD 361 MM=1,KTD
KZA=VEE(MM,3)
IF(KZA-NCON-1)362,363,362
362 KZB=VEE(MM,5)
EFR(KZA)=COEFR(KZB)
363 KZC=VEE(MM,4)
IF(KZC-NCON-1)364,361,364
364 KZD=VEE(MM,6)
EFR(KZC)=COEFR(KZD)
361 CONTINUE
DD 365 MM=1,NCON
CJEFR(MM)=EFR(MM)
365 CONTINUE
IF(JJ-2)633,634,634
633 PCTR(IR)=1.+PCTR(IR)
DD 621 M=1,NCON
WIREE(M,IR)=COEFR(M)+WIREE(M,IR)
621 CONTINUE
GO TO 80
634 SCTR(IR)=1.+SCTR(IR)
DJ 714 M=1,NCON
WIREF(M,IR)=COEFR(M)+WIREF(M,IR)
714 CCONTINUE
80 CONTINUE
IF(JJ-1)925,925,926
925 CCONTINUE
DD 811 MM=1,NCON
WIREE(MM,IR)=WIREE(MM,IR)/PCTR(IR)
311 CCONTINUE
DD 624 M=1,NCON
DD 625 MM=1,NCON
WIREC(M,IR)=Z(M,MM)*WIREE(MM,IR)+WIREC(M,IR)
625 CCONTINUE
624 CCONTINUE
DD 942 MM=1,NCON
WIREC(LCON,IR)=ZS(MM)*WIREE(MM,IR)+WIREC(LCON,IR)
942 CONTINUE
GO TO 678
926 CCONTINUE
DD 812 MM=1,NCON
WIREF(MM,IR)=WIREF(MM,IR)/SCTR(IR)
812 CCONTINUE
DD 636 M=1,NCON
DD 637 MM=1,NCON
WIREG(M,IR)=Z(M,MM)*WIREF(MM,IR)+WIREG(M,IR)
637 CONTINUE
636 CCONTINUE
DD 944 MM=1,NCON
WIREG(LCON,IR)=ZS(MM)*WIREF(MM,IR)+WIREG(LCON,IR)
944 CONTINUE
C WIREB(1...NCON,1...MTIM) CONTAINS V+
C WIRED(1...NCON,1...MTIM) CONTAINS I+
C WIREC(1...NCON,1...MTIM) CONTAINS V- FOR A LOAD OF 50K OHMS ON WIRE MR
C WIREE(1...NCON,1...MTIM) CONTAINS I- FOR A LOAD OF 50K OHMS ON WIRE MR
C WIREF(1...NCON,1...MTIM) CONTAINS I- FOR A LOAD OF 0.01 OHMS ON WIRE MR
C WIREG(1...NCON,1...MTIM) CONTAINS V- FOR A LOAD OF 0.01 OHMS ON WIRE MR
678 CONTINUE
DD 903 MM=1,KTD

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      IF (MR-KREG(MM)) 904,905,904
904  IF (MR-LREG(MM)) 903,905,903
905  JMR=MM
      GO TO 906
903  CJNTINUE
906  IF (JJ-2) 631,632,632
931  VEE(JMR,1)=0.01
      GO TO 600
932  VEE(JMR,1)=50000.
600  CONTINUE
C  MAR IS THE WIRE NUMBER FOR WHICH CURRENT IS DESIRED
C  NMAR IS THE TOTAL WIRE COUNT FOR MAR
      IF (NMAR) 547,547,550
550  DO 547 M=1,NMAR
      DO 548 MM=1,MTIM
      MMAR=MAR(M)
      WCURR=WIREB(MMAR,MM)-WIREF(MMAR,MM)
      WVOLT=WIREB(MMAR,MM)+WIREC(MMAR,MM)-WIREB(LCON,MM)-WIREC(LCON,MM)
      XCURR=WIREB(MMAR,MM)-WIREE(MMAR,MM)
      XVOLT=WIREB(MMAR,MM)+WIREG(MMAR,MM)-WIREB(LCON,MM)-WIREG(LCON,MM)
      IF (NMAR-1) 374,375,374
375  CURRN(MM)=WCURR
      VOLTN(MM)=WVOLT
      CURRM(MM)=XCURR
      VOLTM(MM)=XVOLT
374  WRITE(6,549)MMAR,MM,WCURR
549  FORMAT(7X,29HCURRENT THROUGH LOAD ON WIRE ,13,19HFOR TIME INCREMEN
      T ,13,3HIS ,E10.4)
548  CONTINUE
547  CJNTINUE
      DO 680 MM=1,MTIM
      DO 681 NN=1,NCON
      VSHLD(MM)=2S(NN)*(WIREB(NN,MM)+WIREE(NN,MM))+VSHLD(MM)
681  CJNTINUE
680  CONTINUE
      DO 907 MM=1,KTD
      IF (MR-KREG(MM)) 909,908,909
909  IF (MR-LREG(MM)) 907,910,907
907  CJNTINUE
910  IF (KREG(MM)-NCON) 720,720,918
908  IF (LREG(MM)-NCON) 912,912,911
720  DO 721 NN=1,MTIM
      FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-WIREB(KREG(MM),NN)-
      WIREC(KREG(MM),NN)
      FCURR(NN)=WIREB(MR,NN)-WIREF(MR,NN)
      WRITE(6,914)NN,FVOLT(NN),FCURR(NN)
721  CJNTINUE
      GO TO 921
912  DO 913 NN=1,MTIM
      FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-WIREB(LREG(MM),NN)-
      WIREC(LREG(MM),NN)
      FCURR(NN)=WIREB(MR,NN)-WIREF(MR,NN)
      WRITE(6,914)NN,FVOLT(NN),FCURR(NN)
914  FORMAT(2X,43HTHEVENIN EQUIVALENT VDC FOR TIME INCREMENT ,13,
      64H IS ,E10.3,29H- - THE CORRESPONDING ISX IS ,E10.3)
913  CONTINUE
      GO TO 921
911  DO 915 NN=1,MTIM
      FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-VSHLD(NN)
      FCURR(NN)=WIREB(MR,NN)-WIREF(MR,NN)

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WRITE(6,917)NN,FVOLT(NN),FCURR(NN)
917 FORMAT(2X,43HTHEVENIN EQUIVALENT VDC FOR TIME INCREMENT ,I3,4H IS
&,E10.3,29H- - THE CORRESPONDING ISX IS ,E10.3)
915 CONTINUE
GO TO 921
918 DO 919 NN=1,MTIM
FVOLT(NN)=WIREB(MR,NN)+WIREC(MR,NN)-WIREB(KREG(MM),NN)-
&WIREC(KREG(MM),NN)
FCURR(NN)=WIRED(MR,NN)-WIREF(MR,NN)
WRITE(6,920)NN,FVOLT(NN),FCURR(NN)
920 FORMAT(2X,43HTHEVENIN EQUIVALENT VDC FOR TIME INCREMENT ,I3,4H IS
&,E10.3,29H- - THE CORRESPONDING ISX IS E10.3)
919 CONTINUE
C FVOLT(1...MTIM) IS THE FINAL VOLTAGE ACROSS LOAD AT MR
C FCURR(1...MTIM) IS THE FINAL CURRENT THROUGH LOAD AT MR
C VSHLD(1...MTIM) IS THE SHIELD POTENTIAL
921 CONTINUE
DO 949 N=1,MTIM
IF(FCURR(N))951,950,951
950 FCURR(N)=1.0E-12
951 ZTHEV(N)=FVOLT(N)/FCURR(N)
WRITE(6,952)N,ZTHEV(N)
952 FORMAT(2X,25HZTHEV FOR TIME INCREMENT ,I3,4H IS ,E10.3)
949 CONTINUE
DO 953 N=1,MTIM
DO=N
ZTIME(N)=DELT*(DD-1.)
953 CONTINUE
C DRAW1, DRAW2, AND DRAW3 ARE PLOT ROUTINES
CALL DRAW2 (1,8,8,20,0,MTIM,0.,2.,XLAB,YLAD,PTLAD,SUBLAD,ZTIME,
&CUPDS)
CALL DRAW2 (1,8,8,20,0,MTIM,0.,2.,XLAB,YLAB,PTLAB,SUBLAB,ZTIME,
&FVOLT)
CALL DRAW2 (1,8,8,20,0,MTIM,0.,2.,XLAB,YLAC,PTLAC,SUBLAC,ZTIME,
&FCURR)
IF(PLDT)366,367,371
366 CALL DRAW1(1,8,8,20,0,MTIM,0.,2.,XLAB,YLAD,PTLAD,SUBLAD,ZTIME,
&CUPDS)
CALL DRAW1(1,8,8,20,0,MTIM,0.,2.,XLAB,YLAB,PTLAB,SUBLAB,ZTIME,
&FVOLT)
CALL DRAW1(1,8,8,20,0,MTIM,0.,2.,XLAB,YLAC,PTLAC,SUBLAC,ZTIME,
&FCURR)
GO TO 367
371 IF(BPLDT)376,373,372
373 CALL DRAW3(1,1,6,6,9,9,XAX,YAX,PTLAE,SUBAA)
CALL DRAW3(2,1,1,23,2,2,TIME,CAPC,1.E-30,0.)
CALL DRAW3(2,1,1,MTIM,0,0,ZTIME,FCURR,0.,0.)
CALL DRAW3(3,1,0,0,0,-200,XYX,XYX,0.,0.)
CALL DRAW3(1,2,6,6,9,9,XAX,ZAX,PTLAF,SUBAA)
CALL DRAW3(2,2,1,23,2,2,TIME,CAPD,1.E-30,0.)
CALL DRAW3(2,2,1,MTIM,0,0,ZTIME,FVOLT,0.,0.)
CALL DRAW3(3,2,0,0,0,200,XYX,XYX,0.,0.)
GO TO 367
376 CONTINUE
372 CONTINUE
367 CONTINUE
WRITE(6,1003)
1003 FORMAT(' WIRE DELT V+ V- (50K) I+ I- (50K) V- (.01
&) I- (.01) VSHLD*')
IF(MTIM-5)368,368,369

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```
368 M5=1
    GO TO 370
369 M5=5
370 DO 1000 N=1,LCON
    DJ 1001 M=1,MTIM,M5
    WRITE(6,1002)N,M,WIREB(N,M),WIREC(N,M),WIRED(N,M),WIREE(N,M),
    &WIREG(N,M),WIREF(N,M),VSHLD(M)
1002 FORMAT(2H ,12,3H ,12,1H ,7E10.2)
1001 CONTINUE
1000 CONTINUE
    WRITE(6,76)
76  FORMAT(' NOTE...ALL UNITS FOR PRINTED VALUES ARE VOLTS, AMPERES O
    &R OHMS')
    STOP
    END
```



#### 4. COMPARISON OF CODE AND EXPERIMENTAL RESULTS

Four shielded cables were used for all tests. Figure 1 is a scaled illustration of the cross-section geometry of the cables, and table I is a list of the relevant parameters. All geometrical parameters were obtained from either the manufacturer's data or physical measurements.

TABLE I. TEST CABLE PARAMETERS

Parameter	Cable			
	A	B	C	D
Wire count	2.0	2.0	4.0	16.0
Wire radii	0.019	0.011	0.032	0.019
Shield radius	0.081	0.081	0.25	0.159
Dielectric constant	2.25	2.25	5.5	2.25
Wire layer radii	0.041	0.041	0.1	0.060 0.125

For the multiwire line, cable impedance is a function of the driving mode and, unlike the single conductor coaxial cable, can be altered by the cable end terminations. Treating the infinitely long line, for the four-wire cable of figure 1, from equation (8),

$$V_1 = Z_{11}i_1 + Z_{12}i_2 + Z_{13}i_3 + Z_{14}i_4 ,$$

$$V_2 = Z_{21}i_1 + Z_{22}i_2 + Z_{23}i_3 + Z_{24}i_4 ,$$

$$V_3 = Z_{31}i_1 + Z_{32}i_2 + Z_{33}i_3 + Z_{34}i_4 ,$$

$$V_4 = Z_{41}i_1 + Z_{42}i_2 + Z_{43}i_3 + Z_{44}i_4 ,$$

$$V_S = Z_{S1}i_1 + Z_{S2}i_2 + Z_{S3}i_3 + Z_{S4}i_4 ,$$

where  $V_N$  and  $i_N$ ,  $N = 1, 2, 3, 4$ , are the voltage and the current for wire  $N$ , and subscript  $S$  references the shield. If the cable is driven in a balanced mode, that is, for  $i_1 = i_2 = -i_3 = -i_4$  and  $i_S = 0$ ,

$$Z_{12,34} = \frac{V_1 - V_3}{2i_1} = Z_{11} - Z_{13} , \quad (48)$$

where  $Z_{12,34}$  is the cable impedance for the balanced driving mode. For the condition that  $i_1 = i_3 = -i_2 = -i_4$  and  $i_S = 0$ ,

$$Z_{13,24} = Z_{11} + Z_{13} - 2Z_{12} . \quad (49)$$

For  $i_1 = -3i_2 = -3i_3 = -3i_4$  and  $i_S = 0$ ,

$$Z_{1,234} = \frac{4}{3} (Z_{11} - Z_{12}) . \quad (50)$$

If the four wires are driven to shield, that is,  $i_1 = i_2 = i_3 = i_4 = -i_S/4$ , then

$$Z_{1234,S} = (Z_{11} + 2Z_{12} + Z_{13} - 4Z_{S1})/4 . \quad (51)$$

Similarly, for the two-wire shielded cable for the balanced driving mode,

$$Z_{1,2} = 2Z_{11} - 2Z_{12} . \quad (52)$$

For the two wires driven to shield,

$$Z_{12,S} = (Z_{11} + Z_{12} - 2Z_{S1})/2 . \quad (53)$$

For the 16-wire, two-layer cable of figure 1, for the conditions that  $i_M = i_N$  for  $M, N = 1, 2, \dots, 5$ ,  $i_J = i_K$  for  $J, K = 6, 7, \dots, 16$ ,

$$\sum_{N=1}^5 i_N = - \sum_{N=6}^{16} i_N , \quad i_S = 0 ,$$

$$Z_{1,\dots,5,6,\dots,16} = \frac{1}{5} \sum_{N=1}^5 (Z_{1N} - Z_{6N}) + \frac{1}{11} \sum_{N=6}^{16} (Z_{6N} - Z_{1N}) . \quad (54)$$

For  $i_M = i_N = 0$ ,  $M, N = 1, 2, \dots, 5$ ,

$$i_J = i_K = -i_S/11, \quad J, K = 6, 7, \dots, 16 ,$$

$$Z_{6,\dots,16,S} = \frac{1}{11} \sum_{N=6}^{16} (Z_{6N} - Z_{SN}) . \quad (55)$$

For  $i_M = i_N = -i_S/5$ ,  $M, N = 1, 2, \dots, 5$ ,

$i_J = i_K = 0$ ,  $J, K = 6, 7, \dots, 16$ ,

$$Z_{1\dots 5, S} = \frac{1}{5} \sum_{N=1}^5 (Z_{1N} - Z_{5N}) \quad (56)$$

If the cable coupling is the EMP mode of through-the-shield signal penetration, then the impedance of the infinitely long line is given by equation (13) with the auxiliary conditions given in section 2. For the two- and four-wire cables, this relationship reduces to equations (53) and (51). Table II is a tabulation of the experimentally determined cable impedances,  $Z_{N,M}$ , and the corresponding values as calculated from data generated by the multiwire cable code.

In section 2, the requirement is imposed that, for the infinitely long cable, the signal penetration results in a wire current distribution that represents a minimum energy density. The consequence of this requirement is demonstrated by calculating the ratio of the current on a single inner layer wire to a single outer layer wire for the two-layer cable of figure 1 as the number of outer layer wires is reduced from 11 to 1: the remaining wires are uniformly distributed about the outer layer circumference. The results are plotted in figure 2. The sign reversal observed between the inner and outer layers is typical of dense, multilayer cables. An investigation of three- and four-layer cables shows a similar current reversal between adjacent layers.

Figure 3 is a schematic of the cable driver designed to test the predictions of the cable code. A significant design deficiency is the inability to measure the wire bundle current prior to cable end interaction. To arrive at  $I_T^+(t)$ , a required input to the multiwire code, certain inferences based on code results must be made. Under resistive cable end loading, the measured waveforms at the wire terminations have a shape matching that of  $I_T^+(t)$  for the period prior to the arrival of the far-end cable reflection. For short-circuit terminations to shield for the wire bundle, the current at any termination is double the corresponding value of  $I^+(t)$ . An examination of the experimental data reveals that the signal coupled through the shield is not a smooth waveform and that the noise level is sufficient to preclude any precise determination of its shape. For the latter reason, a smooth waveform intended only to approximate the general shape of the measured data was used with the code.

TABLE II. EXPERIMENTAL AND THEORETICAL CABLE IMPEDANCE TERMS

Cable	Term	Impedance ( $\Omega$ )	
		Experimental	Theoretical
A	$Z_{1,2}$	76	70
	$Z_{12,S}$	26	28
B	$Z_{1,2}$	128	118
	$Z_{12,S}$	40	39
C	$Z_{12,34}$	38	39
	$Z_{13,24}$	28	28
	$Z_{1,234}$	47	44
	$Z_{1234,S}$	18	21
D	$Z_{1\dots5,6\dots16}$	21	24
	$Z_{6\dots16,S}$	7.8	7.8
	$Z_{1\dots5,S}$	29	35

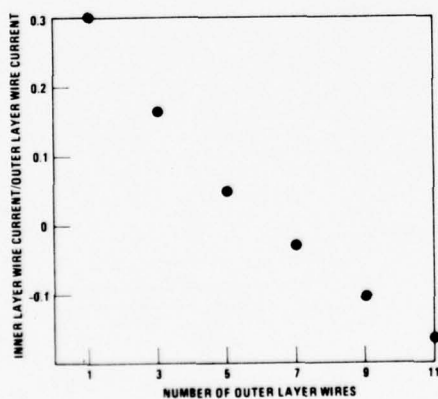


Figure 2. Current reversal on two-layer cable.

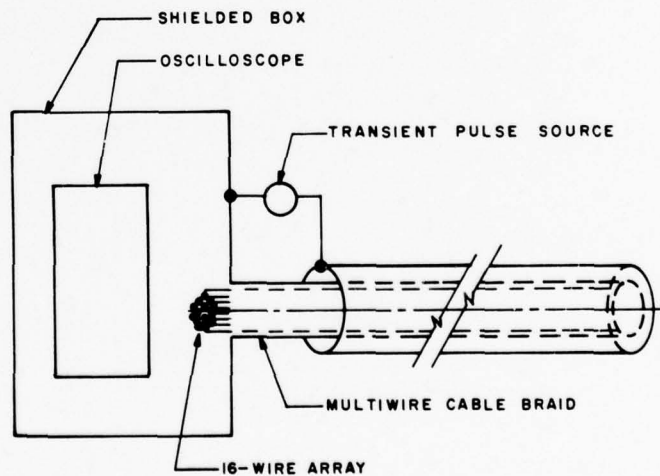


Figure 3. Cable-driver configuration.

The magnitudes of all experimental and theoretical data are related by normalizing the experimental results to a peak driving current of 1 A. The results are normalized by scaling the experimental data for the case of short-circuit wire bundle termination to 2 A. A comparison of the code and the experimental results for a single inner and a single outer layer wire to shield is given in figures 4 and 5 for the case of all wires short-circuited to shield. The open-circuit voltage measurement represents the wire to shield open-circuit voltage for the indicated wire with all remaining conductors short-circuited. The effect of termination lead inductance is shown in figure 6, a set of current measurements employing a short-circuit termination lead length of approximately 10 cm. A similar set of data is presented in figures 7 and 8 for the other extreme in cable end loading--all wires in open-circuit termination. A comparison of the waveform data for the two extremes in termination conditions reveals the significance of the wire end loading in determining the signal. Tables III and IV list the experimental peak amplitude response of all inner layer and four outer layer wires for the loading conditions noted. These data are supplemental to information contained in figures 4 through 8 and indicate the general level of response variability from wire to wire.

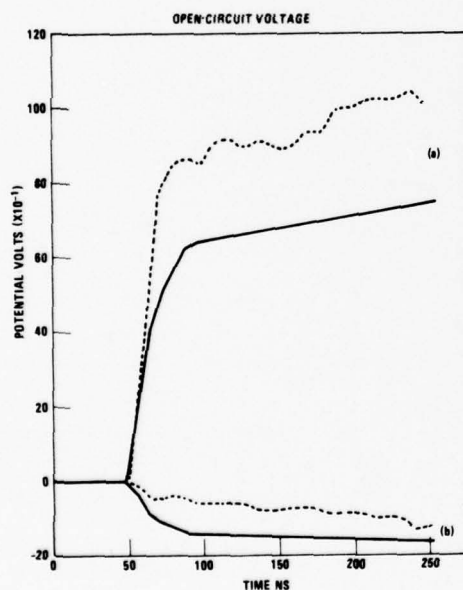


Figure 4. Wire-to-shield potential for (a) single outer and (b) single inner layer wires for 16-conductor cable with remaining wires short-circuited to shield (experimental ..., theoretical—).

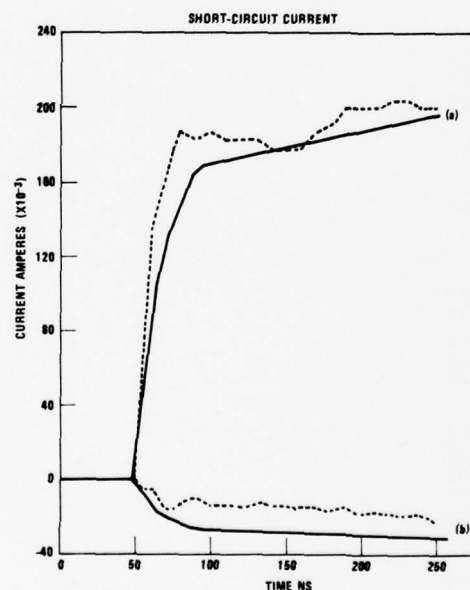


Figure 5. Current on (a) single outer and (b) single inner layer wires for 16-conductor cable with all wires short-circuited to shield (experimental ..., theoretical—).



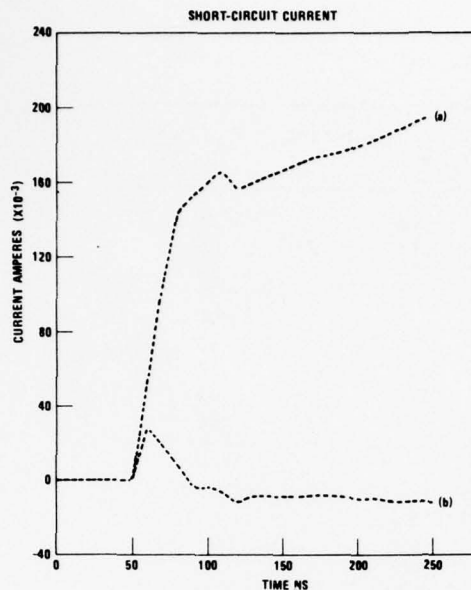


Figure 6. Experimental wire current to shield corresponding to data of figure 5, but with increased termination inductance: (a) single outer layer and (b) single inner layer wire responses.

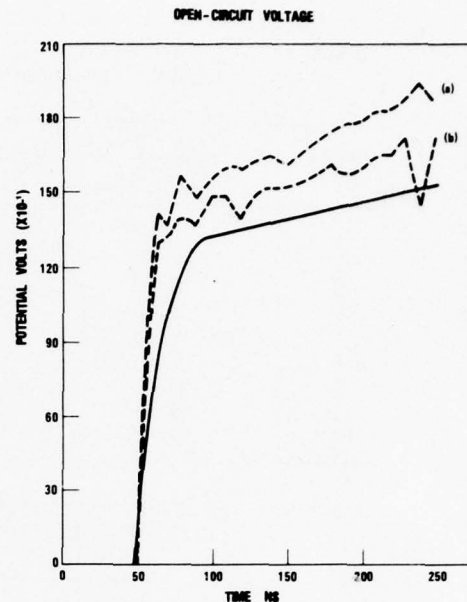


Figure 7. Wire-to-shield potential for (a) single outer and (b) single inner layer wires for 16-conductor cable (two theoretical curves superimposed) for all wires into open-circuit termination (experimental ..., theoretical —).

Figure 8. Current on (a) single outer and (b) single inner layer wires short-circuited to shield for 16-conductor cable with all other wires open-circuit termination (experimental ..., theoretical —).

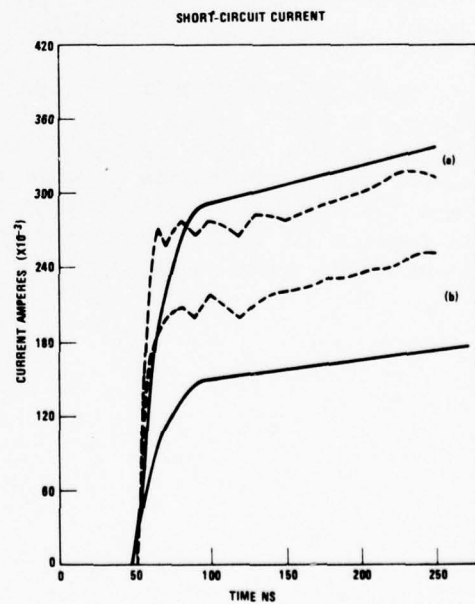


TABLE III. PEAK AMPLITUDE RESPONSE OF 16-WIRE CABLE UNDER SHORT-CIRCUIT END-LOADING CONDITIONS

Wire No.	Open-circuit voltage ( $V_{OC}$ ) (V)	Short-circuit current ( $I_{SX}$ ) (mA)	$V_{OC}/I_{SX}$ ( $\Omega$ )
1	1.0	18	56
2	1.05	19	55
3	0.70	13	54
4	0.40	7	57
5	0.65	12	54
6	11.0	220	50
9	10.0	190	53
11	9.5	195	49
13	10.0	180	56

TABLE IV. PEAK AMPLITUDE RESPONSE OF 16-WIRE CABLE UNDER OPEN-CIRCUIT END-LOADING CONDITIONS

Wire No.	Open-circuit voltage ( $V_{OC}$ ) (V)	Short-circuit current ( $I_{SX}$ ) (mA)	$V_{OC}/I_{SX}$ ( $\Omega$ )
1	16.5	225	73
2	16.5	225	73
3	16.5	225	73
4	17.0	230	74
5	17.0	230	74
6	19.0	305	62
9	18.0	295	61
11	17.5	295	59
13	17.0	280	61

To avoid the difficulties inherent in the cable-driver design of figure 3, the configuration of figure 9 was used to drive, in this instance, the four-wire cable of figure 1. The effect of distributed series cable resistance is compensated for in the  $I^+(t)$  driving waveform. The open-circuit voltage and the short-circuit current are given in figures 10 to 15 for a single wire to shield with each remaining wire identically terminated with capacitors (0.1  $\mu$ F, 1500 pF, or 80 pF).

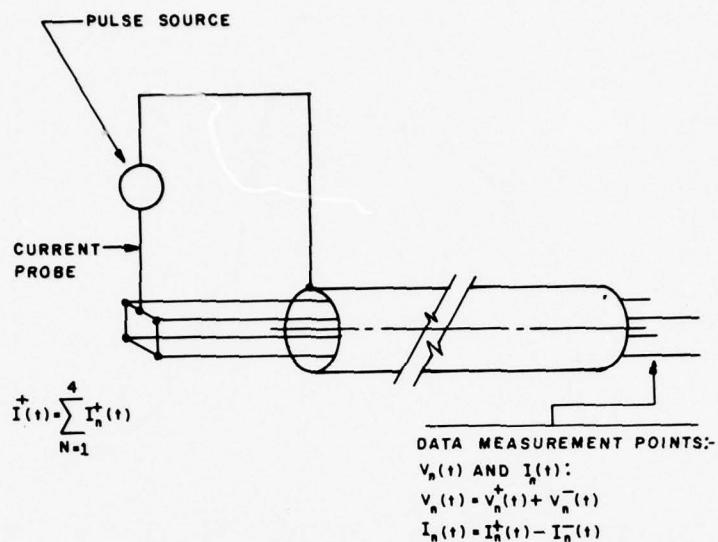


Figure 9. Modified cable-driver test configuration to permit measurement of all  $I^+(t)$  current components.

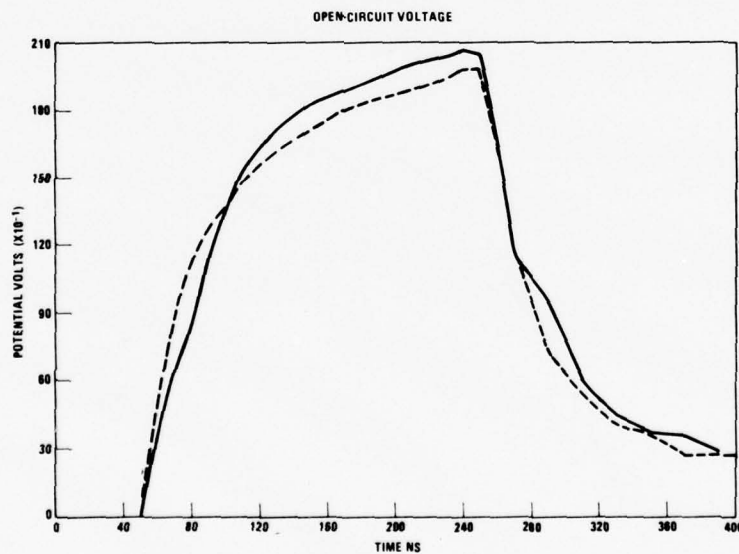


Figure 10. Single-wire potential to shield for four-wire cable with remaining wires terminated to shield with  $0.1\text{-}\mu\text{F}$  capacitors (experimental ..., theoretical —).

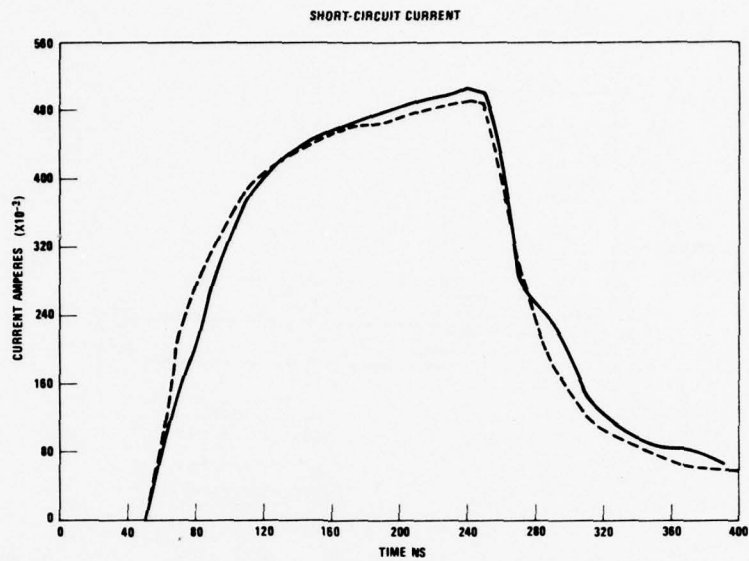


Figure 11. Single-wire current to shield for four-wire cable with remaining wires terminated to shield with 0.1- $\mu$ F capacitors (experimental ..., theoretical —).

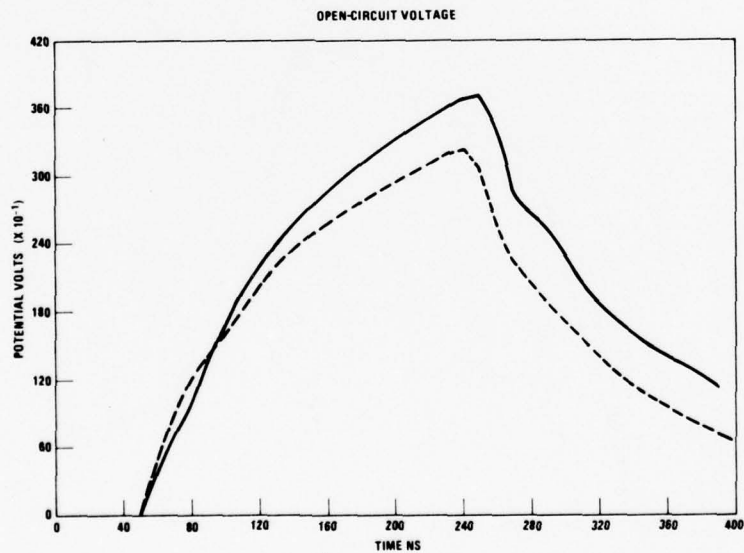


Figure 12. Single-wire potential to shield for four-wire cable with remaining wires terminated to shield with 1500-pF capacitors (experimental ..., theoretical —).

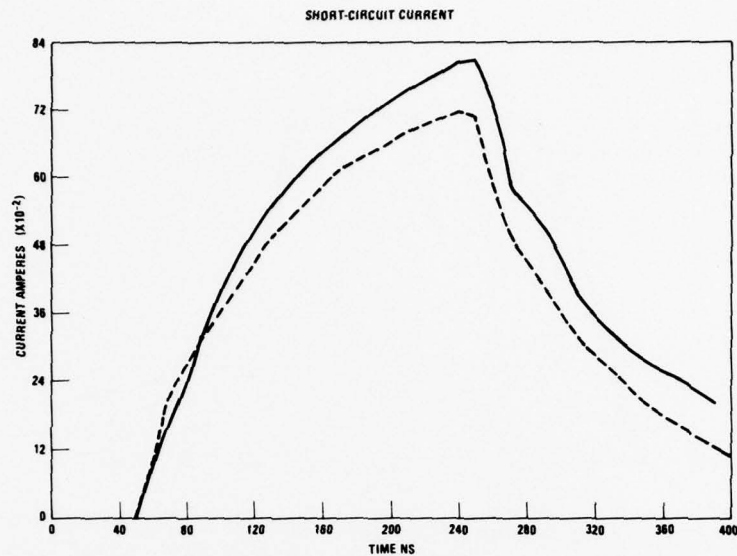


Figure 13. Single-wire current to shield for four-wire cable with remaining wires terminated to shield with 1500-pF capacitors (experimental ..., theoretical —).

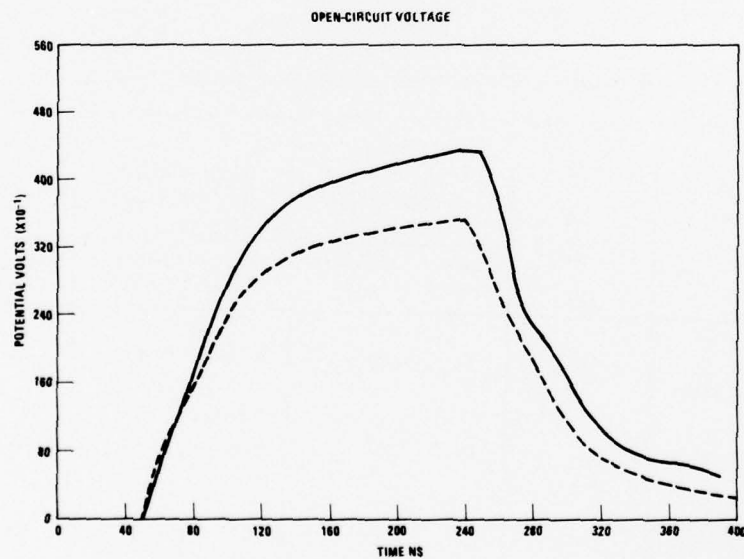


Figure 14. Single-wire potential to shield for four-wire cable with remaining wires terminated to shield with 82-pF capacitors (experimental ..., theoretical —).



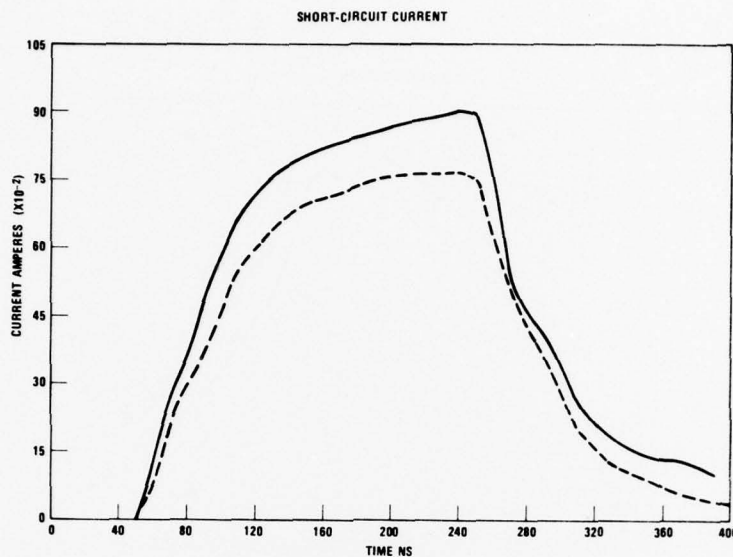


Figure 15. Single-wire current to shield for four-wire cable with remaining wires terminated to shield with 82-pF capacitors (experimental ..., theoretical —).

An exhaustive series of tests was performed with the four-wire cable under resistive end loading. Since the impedance of a resistive load is independent of frequency, no wave shape distortion is incurred, and all data can be tabulated by magnitude. Table V is representative of the resistively loaded cable results.

TABLE V. FOUR-WIRE CABLE RESPONSE UNDER RESISTIVE END LOADING

Measured conductor pair	Remaining wire loads ( $\Omega$ )	Drive current $i^+ = \sum_{N=1}^4 i_N^+$ (A)	Open-circuit voltage ( $V_{OC}$ ) (V)		Short-circuit current ( $I_{SX}$ ) (A)		$V_{OC}/I_{SX}$ ( $\Omega$ )	
			Experi-mental	Theoret-ical	Experi-mental	Theoret-ical	Experi-mental	Theoret-ical
1-S	2-S = 0 3-S = 0 4-S = open	1	25	27	0.56	0.62	45	44
1-S	2-S = 0 3-S = open 4-S = 0	1	20	21	0.47	0.52	43	40
1-S	2-S = open 3-S = open 4-S = open	1	36	44	0.75	0.90	48	49
1-S	2-S = 0 3-S = 0 4-S = 0	1	20	20	0.48	0.50	42	40
1-2	3-S = 0 4-S = open	1	4.2	4.9	-	0.074	-	66

A similar series of tests was performed with the two-layer cable under resistive end loading by using the configuration of figure 9. The multiwire cable code was modified to permit the imposition of an arbitrary  $I^+$  current component on all wires, and a resistor network was added to the pulse generator to permit the injection of an identical current on all wires. This is a contrived current distribution, not at all related to the conditions demonstrated by figure 2 for a through-the-shield coupling condition and as such does not relate to what can be anticipated under an EMP. Nevertheless, the results obtained are useful for testing all provisions of the multiwire cable code, except for the algorithm that establishes the  $I^+$  distribution. The results are given in table VI. A series of curves was generated for the two-layer cable under resistive end loading (fig. 16 to 20). These represent the measured and predicted voltages across a single-wire load to shield ranging in value from a short-circuit to an open-circuit termination.

Table VII compares the code-predicted source impedance and the point on curves where the load voltage is half the open-circuit value (the experimental source impedance).

Table VIII lists the experimental and theoretical responses of the cable of figure 1(a) under the loading conditions indicated.

TABLE VI. SIXTEEN-WIRE CABLE RESPONSE UNDER RESISTIVE END LOADING

Measured conductor pair	Remaining wire loads ( $\Omega$ )	Drive current $I^+ = \sum_{N=1}^{16} i_N^+$ (A)	Open-circuit voltage ( $V_{OC}$ ) (V)		Short-circuit current ( $I_{SX}$ ) (A)		$V_{OC}/I_{SX}$ ( $\Omega$ )	
			Experimental	Theoretical	Experimental	Theoretical	Experimental	Theoretical
1-S	2 . . . 5-S = 0 6 . . . 10-S = 39 11 . . . 16-S = open	1	9.1	10.0	0.18	0.18	51	56
1-S	2 . . . 5-S = 0 6 . . . 16-S = open	1	10.2	11.6	0.20	0.21	51	56
5-S	1 . . . 4-S = 0 6 . . . 10-S = 0 11 . . . 16-S = open	1	8.6	8.4	0.17	0.15	51	56

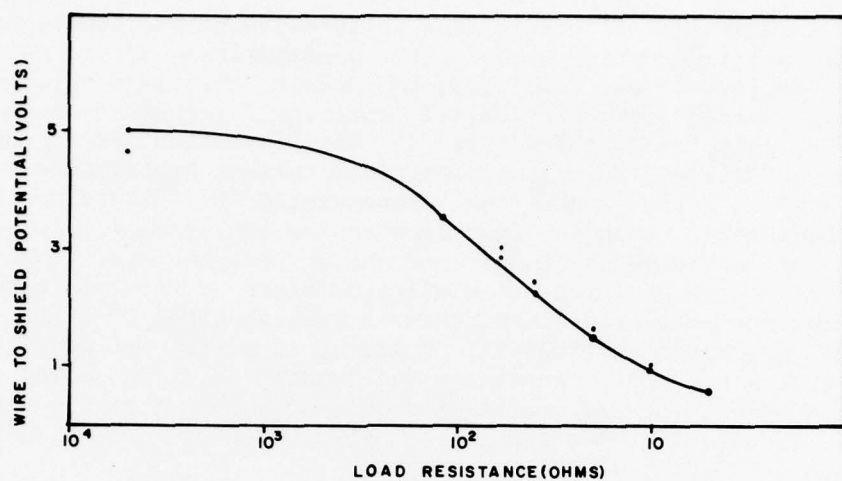


Figure 16. Wire 6 response for 16-wire cable with remaining wires short-circuited to shield (experimental —, theoretical ...).

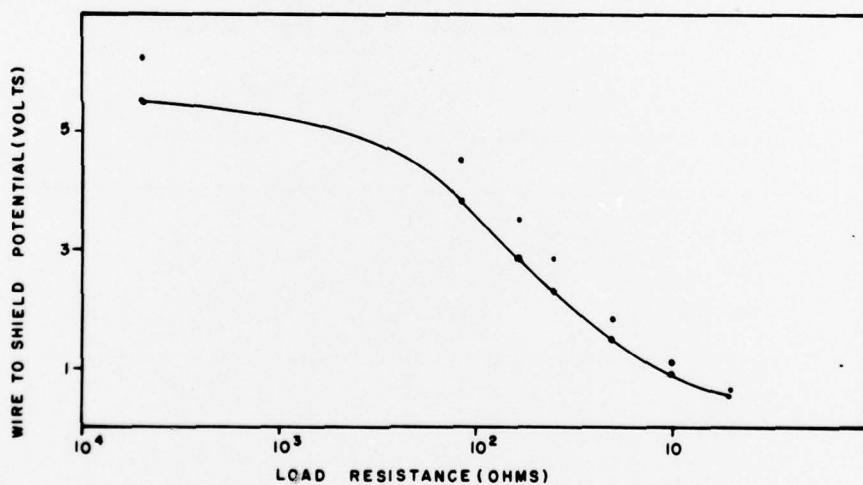


Figure 17. Wire 1 response for 16-wire cable with remaining wires short-circuited to shield (experimental —, theoretical ...).

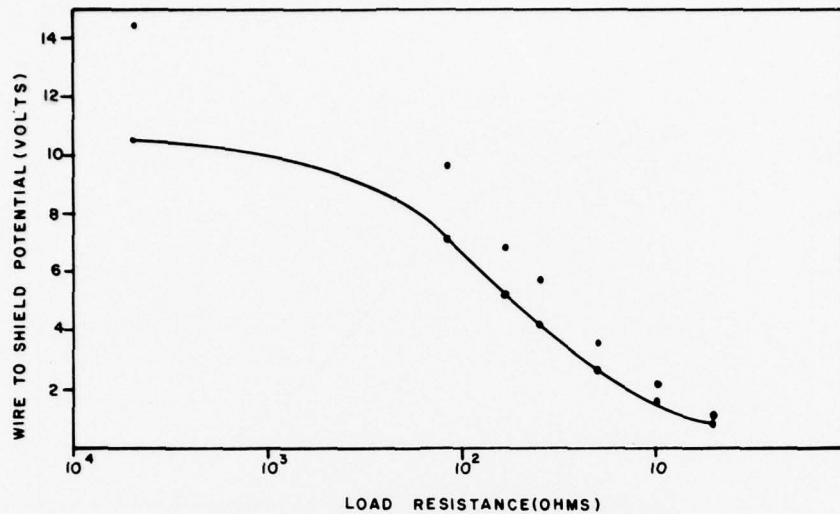


Figure 18. Wire 1 response for 16-wire cable with wires 2 to 5 open-circuit termination and remaining wires short-circuited to shield (experimental —, theoretical ...).

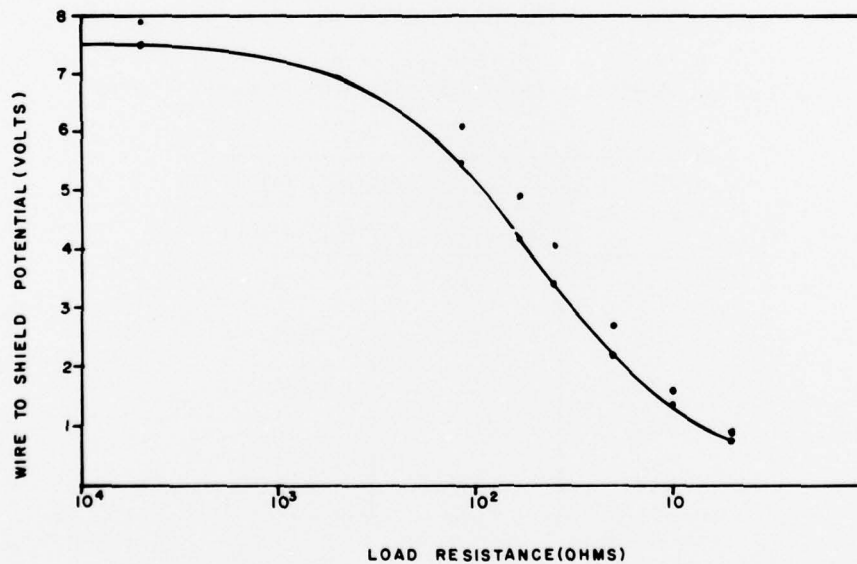


Figure 19. Wire 6 response for 16-wire cable with wires 1 to 5 open-circuit termination and remaining wires short-circuited to shield (experimental —, theoretical ...).

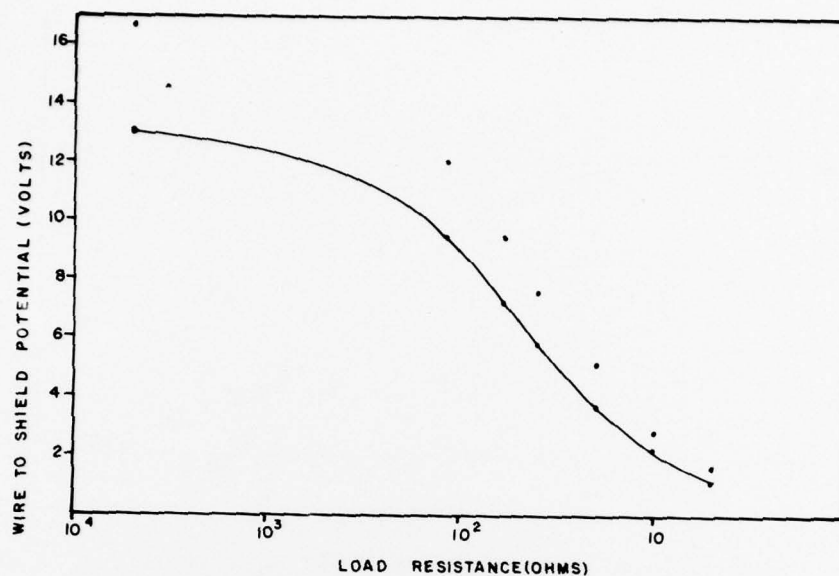


Figure 20. Wire 6 response for 16-wire cable with remaining wires open-circuit termination (experimental —, theoretical ...).

TABLE VII. SOURCE IMPEDANCE FOR CABLES OF FIGURES 16 TO 20

Figure No.	Source impedance ( $\Omega$ )	
	Experimental	Theoretical
16	48	38
17	58	51
18	58	60
19	49	41
20	49	48



TABLE VIII. TWO-WIRE CABLE RESPONSE UNDER RESISTIVE END LOADING (FIG. 1a)

Measured conductor pair	Remaining wire loads ( $\Omega$ )	Drive current $I^+ = \sum_{N=1}^2 i_N^+$ (A)	Open-circuit voltage ( $V_{OC}$ ) (V)		Short-circuit current ( $I_{SX}$ ) (A)		$V_{OC}/I_{SX}$ ( $\Omega$ )	
			Experimental	Theoretical	Experimental	Theoretical	Experimental	Theoretical
1-S	2-S = 0	1	43	40	0.93	1.0	46	40
1-S	2-S = open	1	48	55	1.0	1.3	48	42

## 5. SUMMARY

An approach is presented to develop an equivalent circuit compatible with a circuit code for any conductor pair that forms part of a shielded multiwire array. The multiwire shielded cable problem was analyzed as part of the Army MSEP. The theory as reflected by the code of section 3 was compared with the experimental data for four test cables. The theory verification data fall into two groups:

a. Data that test the provisions of the infinitely long cable predictions. These encompass measurements to validate the impedance matrix terms and the  $I^+$  current distribution provisions.

b. Data that test the finite cable end loading interactions. These include the cable response to both reactive and resistive terminations.

The theory is sufficiently developed to allow the preliminary code to be extended to encompass all effects necessary for an EMP assessment program.

## 6. DISCUSSION

Electromagnetic pulse coupling codes capable of dealing with such omnipresent penetrators as antennas, wires, and cables form an integral part of any comprehensive program of vulnerability assessment and hardening. Because the typical coupling code operates in the frequency domain and any circuit analysis code with which it must interface operates in the time domain, a difficulty arises. The most common solution is to employ the coupling code to develop a Thevenin or Norton equivalent circuit. The resultant complex source impedance can in many cases be translated into a circuit code compatible L-R-C network only

with great difficulty, if it can be done at all. Any approach that eliminates the need for developing a source impedance model greatly facilitates the use of such coupling codes. The results presented here on the development of a multiwire shielded cable capability--a capability that can be extended to the single-wire coaxial cable, since it performs all solutions in the time domain--can be used to avoid the source impedance difficulty. Although the approach taken is oriented toward the development of a Thevenin equivalent circuit, the multiwire theory provisions can be readily incorporated into an existing circuit analysis code. Or the development can be extended along the lines indicated in the theory section to build circuit component capability into the multiwire code. The significant difference between interfacing a coaxial cable code like FREFLD with the multiwire code and interfacing it directly with a circuit analysis code (like NET-2) is that the former interface requires only the terminated current component,  $I^+(t)$ , and the latter requires a current or a voltage source along with a source impedance model.

Although the present development was intended to deal solely with the shield penetration problem, a redefinition of the conditions for establishing the initial,  $I^+(t)$ , wire current distribution permits a much greater utility of the results. The approach can be readily extended to cover such problem areas as cross talk among conductors and penetration into combinations of shielded and unshielded cabling where the cable bundle coupling can be approximated as a point source rather than as a distributed excitation.

A fundamental problem in applying the code or in attempting to correlate experiment with theory is the poor geometrical stability of many multiwire cables. The four-wire cable (a standard power line with an added external braid) represents as severe an example of this problem as will be typically encountered. The cumulative effect of geometrical instability as the number of wires increased was at the onset uncertain. A comparison of the difference between experiment and theory for the four test cables shows no marked tendency toward a decrease in correlation with increasing wire count. This result is particularly significant since the code is intended to handle cables containing more than 50 wires.

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